1 Introduction and review of linear and non-linear approaches in QCD

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1.1 Non-perturbative approaches

One of the challenges in quantum chromodynamics (QCD) is the description and understanding of high-energy scattering on protons and nuclei. Even for high energies and large Q^2 in deep inelastic electron scattering a nonperturbative framework may be necessary. For the transverse structure function the $q\bar{q}$ dipole in the photon can be large and the saturation scale Q_s is small for the energies we discuss. In the following I will present the main features of such an approach, which of course will also include the perturbative aspects.

The most important phenomenon observed in high-energy scattering is the rise of the total cross sections with increasing c.m. energy. While the rise is slow in hadronic reactions of *large* particles such as protons, pions, kaons, or real photons, it is steep if one *small* particle is involved such as an incoming virtual photonor an outgoing charmonium. This energy behavior is best seen in the proton structure function $F_2(x, Q^2)$. With increasing photon virtuality Q^2, the increase of $F_2(x, Q^2)$ towards small Bjorken x becomes significantly stronger. It is tempting to test the growth of the structure function with nuclei. In the following I will resume my work with Shoshi, Steffen and Dosch which is published in two main papers [1, 2]. For references to other work please see these two papers.

In the two-pomeron model of Donnachie and Landshoff the energy dependence of the cross sections at high energies results from the exchange of a soft and a hard pomeron, the first dominates in hadron-hadron and γ^*p reactions at low Q^2 and the second in γ^*p reactions at high Q^2. The two pomerons may be related to a glueball trajectory, which is inherently nonperturbative, and a gluon ladder à la BFKL, which includes the perturbative aspects. The two-pomeron model, however, does not contain parton saturation nor unitarity effects. A model motivated by the concept of parton saturation is the one of Golec-Biernat and Wüsthoff which allows very successful fits to γ^*p data, but cannot be applied to hadron-hadron reactions. B. Kopeliovich [3] has found a successful description of dipole nucleon scattering which can be used for hadron-nucleon scattering and DIS with moderate Q^2.

In ref. [1] we have combined perturbative and non-perturbative QCD to compute high-energy reactions of hadrons and photons with special emphasis on saturation effects that manifest S-matrix unitarity. We follow the *functional integral approach* to high-energy scattering of Nachtmann, in which the S-matrix element factorizes into the universal correlation of two light-like Wegner-Wilson loops S_{DD}. The light-like Wegner-Wilson loops describe color dipoles given by the quark and antiquark in the meson or photon projectile and the quark and diquark in the baryon target. This approach treats projectile and target symmetrically. S-matrix unitarity is respected as a consequence of a matrix cumulant expansion and the Gaussian approximation of the functional integrals. The resulting dipole cross sections do not show Glauber-like behavior with the dipole size as in the Golec Biernat model. The loop-loop correlation function S_{DD} is expressed in terms of the gauge invariant bilocal gluon field strength correlator integrated over two connected minimal surfaces. Due to the symmetric treatment of the two dipoles this formalism can explicitly investigate the

dependence on the impact parameter of the two scattering partners.

The gluon field strength correlator has a non-perturbative and a perturbative component. The *stochastic vacuum model* of Dosch and Simonov is used for the non-perturbative low frequency background field and *perturbative BFKL gluon exchange* for the high frequency contributions. This combination allows us to describe long and short distance correlations in agreement with Euclidean lattice calculations of the static quark-antiquark potential with color-Coulomb behavior at short distances and confining linear rise at long distances. We have tried to model both components in AdS/QCD, but the long range loop-loop correlation cannot be established on a classical level, since the connecting surface in 5 dimensions breaks off at large distances [4].

Energy dependence into the loop-loop correlation function S_{DD} is introduced by hand in order to describe simultaneously the energy behavior in hadron-hadron, photon-hadron, and photon-photon reactions involving real and virtual photons as well. Motivated by the two-pomeron picture of Donnachie and Landshoff, we ascribe to the soft and hard component a weak and strong energy dependence, respectively. The parameter describing the energy dependence of the perturbative correlation function is very large because we include *multiple gluonic interactions*. In ref. [1] we have considered not only the dependence of the dipole cross section on dipole size with increasing energy and the resulting k_t-saturation, but also the scattering amplitudes in impact parameter space, where the S-matrix unitarity imposes rigid limits on the impact parameter profiles such as the *black disc limit*. We present profile functions for longitudinal photon-proton scattering that provide an intuitive geometrical picture for the energy dependence of the cross sections. The profile function first becomes greyer, turns black and then increases in transverse size. Using a leading twist, next-to-leading order DGLAP relation, we have estimated the *impact parameter dependent gluon distribution* of the proton $xG(x, Q^2, |\vec{b}_\perp|)$ from the profile function for longitudinal photon-proton scattering. We have not found saturation of the profile function at HERA energies, but at higher energies $xG(x, Q^2, |\vec{b}_\perp|)$ does saturate as a manifestation of the S-matrix unitarity.

In the same framework we have studied the unintegrated gluon distribution $xG(x, k_t)$ as function of transverse momentum for increasing energies [2]. The key tool to get to the unintegrated gluon distribution is the possibility to rewrite the non-perturbative scattering of an artificial external dipole as a superposition of perturbative contributions. In other words the string of the projectile dipole can be decomposed mathematically in a superposition of dipoles of smaller sizes, from which the unintegrated gluon distribution can be extracted.

The long range confining character of the non-perturbative field strength correlators determines the low k_t behavior of the gluon structure function of the hadron as $xG(x, k_t) \propto 1/k_t$. In the low momentum limit $xG(x, k_t) \cdot k_t$ converges towards a constant independent of x, related to the size of the hadron. The cross-over from the nonperturbative region to the perturbative region occurs at around $k_t = 1\,\text{GeV}$ at x-values $10^{-4} < x < 10^{-2}$.

On a more fundamental level Feng Yuan and myself [5] have analysed correlations of Wilson lines in vacuum as one approaches the light cone from space-like distances. The dominant terms of the near light cone Hamiltonian for the Wilson lines define a field theory in 2+1 dimensions. In the limit of small x, the SU(3) QCD for Wilson lines reduces to a critical Z(3) theory with a diverging correlation length $\xi(x) \propto x^{-1/(2\lambda_2)}$ where the exponent $\lambda_2 = 2.52$ is obtained from the center group Z(3) of SU(3). We conjecture that the dipole wave function of the virtual photon behaves as the correlation function of Wilson lines in the vacuum. For transverse sizes smaller than the correlation size it scales like $\Psi \propto 1/(x_t)^{1+n}$ with $n = 0.04$ and for distances larger than the correlation length it decays exponentially

which makes this region negligible. For F_2 we integrate the square of the photon wave function weighted with a dipole proton cross section of fixed size R_0 independent of x. All the energy dependence is absorbed into the photon. Because of the aproximate conformality of the dipole wave function ($n \approx 0$), the result depends only on $R_0^2/\xi(x)^2 \propto R_0^2 x^{1/\lambda_2}$, i.e. the saturation scale varies as as $Q_s^2 = Q(x_o)^2(x0/x)^{1/\lambda_2}$. The critical index in this theory is a characteristic feature of Z(3) theory i.e. the center group of SU(3) in an external field given by the light quarks. This is very different from the perturbative color glass condensate where Q_s depends on the running coupling similarily to the power behaviour of BFKL.

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2 Nuclear quarks and gluons

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2.1 Nuclear gluons

Historically, the very accurate measurements of the NMC-group of DIS on tin and carbon nuclei has allowed to extract the gluon distribution from the scaling violation in $F_2(A)$. This has been done by Gousset and myself [1] for the first time. This analysis shows an enhancement of 10% i.e. antishadowing for $x \approx 0.1$ and the same amount of shadowing, namely also 10% at $x \approx 0.01$. A high experimental accuracy is demanded, therefore only a trend can be established. This study aimed to support the use of nuclear beams which is as important now as at the time when HERA was working, because we need nuclear structure function to analyse heavy ion experiments at RHIC and LHC. The asymptotic calculation of heavy charmonium production on nuclei is often proposed as another method to extract the nuclear gluon distribution based on the gluon-gluon fusion process. As shown in various papers by Kopeliovich this production is more complicated especially for the J/Ψ because of initial and final state effects. Measurements of the gluon distribution would give an experimental window on the importance of gluonic effects in nuclear binding. Very little is known about the role of gauge fields in nuclei. In a Wilsonian view of the nucleus, of course, the long time and long range fluctuations in the nucleus should be describable by nucleons and their hadronic interactions. But this is no longer true if one approaches energy or length scales of $1\,\mathrm{GeV}$ or $0.2 - 0.5\,\mathrm{fm}$. In general we associate the energy transfer ν with the time resolution and the virtual momentum Q with the spatial resolution. Very nice studies at JLAB have shown the duality between a hadronic and partonic description of DIS. The short time resolution of DIS experiments on nuclei makes it possible that the naive picture of the nucleus with quarks confined in nucleons makes no more sense. On short time scales the tunneling of quarks from one nucleon to the next makes a much more colorful picture of the nucleus than the mean-field picture of the shell model suggests. In various schemes [2, 3] I have explored and speculated about a picture of the nucleus where this sort of color conductivity plays an important rule for nuclear phycsics. Higher quark clusters with more than three quarks may play an important role in the intermediate density region of baryonic matter from low to high density. These color neutral clusters do not allow to separate the final state interactions as easily as in the case where the quark is ejected out of a nucleon. The comovers of the quark in a six-quark cluster can interact with the ejected quark since they move in the same rapidity region. The same criticism applies to meson cloud models (the famous pion cloud) at small x. Cluster models have their strong point for a fixed target machine like JLAB, where the large x-region can be studied with great accuracy.

We have studied an abelian QED model [4] where the nucleon is replaced by an atom and the nucleus by a molecule, i.e. we have analysed the structure function of the photon in the H_2-molecule and compared it with the structure function in the H-atom. The electron orbits of the hydrogene atoms in the molecule are polarized and modified by the electron exchange interaction leading to a suppression of photons at small x. At the momentum corresponding to the relative distance of the two protons a small antishadowing peak is

visible [4]. In analogy, gluon antishadowing in the region $x = 0.1$ may indicate the distance $\Delta r \approx 2\,\mathrm{fm}$ between the centers of the nucleons which act as color sources of common gluon fields between nucleons. A covalent binding of quarks may manifest itself as a density dependent lack of long range gluons at $x < 0.1$ similarily to the deformation of the photon cloud in the hydrogene molecule. In addition, in non-abelian QCD one expects at small x that the gluons from different nucleons overlap and merge. Both of these effects have also an interpretation in the nuclear rest frame in terms of the absorption of various partonic components in the wave function of the photon.

During the last ten years the few available data have been used to manufacture nuclear structure functions and evolve them to high Q^2. In a careful analysis one has to respect the large errors of the starting distribution at low Q^2 for the nuclear gluon distributions and also the larger x-region has to be included correctly - at least the fact that the nuclear gluon distribution [5] is more strongly affected by Fermi-motion of the nucleons than the quark distribution, since it has a stronger decrease at large x. Enhancement of the nuclear gluon distribution sets in already at $x = 0.5$ which may be of importance for charmonium production at JLAB [5]. The leading twist analysis we proposed in ref. [1] may have problems, because of the importance of higher twist terms at small x, as we know them from the proton structure function F_2.

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3 Jets and current fragmentation

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3.1 Jet evolution in hot and cold matter

High energy probes may be used to analyse the matter which they transverse. Jet tomography has become very popular in heavy ion physics where the plasma as the transient product of the collision of two relativistic nuclei is the object of analysis. We call this matter hot, since the plasma has temperatures of more than 200 MeV, i.e. above the critical or cross over temperature from hadronic degrees of freedom to quark-gluon degrees of freedom. Electron -nucleus jet production can help to test our understanding of jet propagation in cold matter, which should be adressed in a similar way. We will discuss jet propagation in hot matter first.

Theoretical model building has concentrated so far on the energy loss of partons in dense matter, an effort, which has been triggered by the astonishing suppression ratios of pions and other particles produced in Au-Au collisions at RHIC at high transverse momentum and central rapidities. Comparing the π-production cross section in these hard nucleus-nucleus collisions with the expected rate from hard nucleon-nucleon collisions, Phenix and Star collaborations have deduced that in central collisions the suppression reaches factors of five and is more or less constant up to large momenta $p_\perp \approx 14\,\mathrm{GeV}$. A common interpretation is partonic energy loss where hadronization occurs outside of the hot zone and is not affected by the medium. There is no doubt that gluon radiation plays an important role for the energy loss and the parton evolution at RHIC and the LHC. The respective virtualities of partons are around $Q = 20\,\mathrm{GeV}$ and $Q = 100\,\mathrm{GeV}$. In our modeling of jet evolution [1, 2] the parton shower is treated together with the propagation of the parton in the medium which is more realistic because of the relevant time scales. A typical shower at RHIC lasts about $\tau_{evo} = 2\,\mathrm{fm}$. The non-perturbative part of hadronization involves the decay of the resonances at the preconfinement scale $Q_0 = 1 - 2\,\mathrm{GeV}$ into 3-4 pions. The lifetime of the plasma can be estimated $\tau_c = 3.3\,\mathrm{fm}$. Comparing the two time estimates, we see that at the end of the evolution at RHIC resonances interact with hadronic resonance matter. This process can be described by a hadronic theory with cross sections slightly larger than hadronic cross sections in vacuum. Because of these large cross sections, absorptive effects play a decisive role in the observed suppression of hadrons in RHIC experiments. We have advocated two scenarios. Scenario 1 uses the conservative radiative energy loss obtained from QCD and includes prehadron formation and resonance absorption. Scenario 2 tunes up the energy loss parameter to fit the data. Phenomenologically, we have extrapolated both scenarios to LHC and wait now for the LHC data to decide. We have calculated for both scenarios the hadron suppression in Pb-Pb collisions at LHC with $\sqrt(s) = 5.5$ TeV, a virtuality of $Q = 100\,\mathrm{GeV}$ and an initial temperature of $T_0 = 500\,\mathrm{MeV}$. In the LHC case the large virtuality favours a shower lifetime which is longer than the plasma lifetime and both lifetimes are longer than the interaction zone of the two nuclei, therefore we do not expect that resonances play an important role there. The main advantage of LHC is the large production rate of jets. Therefore we also made predictions for the jet composition down to very small momentum fractions. Both scenarios adjusted to the higher temperature

and virtualities can be analysed, since the parametric dependences on T and Q are under control.

Our model [1] works as follows: The parton produced in a hard process radiates successively to reduce its virtuality and become on mass-shell. This parton shower is modified by scattering in the medium. Because both terms enter the same equation one cannot separate scattering and radiation. This equation includes truly radiative energy loss, but without coherence. Quark fragmentation at RHIC and gluon fragmentation at LHC should give the essential results. The indices on the fragmentation functions and the splitting functions can then be dropped and the formalism becomes simpler.

For the in-medium fragmentation function $D^m(x, Q^2)$ we include into the DGLAP evolution the scattering term $S(x, Q^2)$.

$$\frac{\partial\, D^m(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{\mathrm{d}z}{z} P(z) D^m\left(\frac{x}{z}, Q^2\right) + S(x, Q^2) \tag{1}$$

with

$$S(x, Q^2) \simeq f \frac{n_g \sigma \langle q_\perp^2 \rangle}{2 m_s Q^2} \left(D(x, Q^2) + x \frac{\partial D}{\partial x}(x, Q^2) \right). \tag{2}$$

The quantity appearing in the scattering term is the jet transport parameter

$$\hat{q} \simeq \bar{n} \bar{\sigma} \langle q_\perp^2 \rangle, \tag{3}$$

which describes the mean acquired transverse momentum of the parton per unit length.

To allow a direct fit of experimental data with only parton energy loss, we introduce a possible enhancement factor f in the scattering term. The scattering term is most relevant at small virtualities $Q \simeq Q_0$ and consequently we have used the scale Q_0 in α_s to arrive at an upper boundary for $\hat{q}$. More explicitly, these expressions give $\hat{q} = 0.5\,\mathrm{GeV}^2\,/\,\mathrm{fm}$ for a temperature of $T = 0.3$ GeV for RHIC and $\hat{q} = 5.2\,\mathrm{GeV}^2\,/\,\mathrm{fm}$ for $T = 0.5\,\mathrm{GeV}$ corresponding to LHC. As shown in ref. [1] we can fit the RHIC data including prehadron absorption in the final state resonance gas. The prediction for LHC gives an $R_{AA} \approx 0.4$. If we use an enhancement factor $f = 8$ which is beyond any higher order QCD correction, the measurement of hadrons with high transverse momentum would be totally suppressed at LHC.

The hadronization mechanism of quarks in deep inelastic scattering on nuclei has been extensively studied for Hermes energies as a function of energy transfer, hadronic momentum fraction and photon virtuality in ref. [3, 4]. We have looked at the induced hadronic mean transverse momentum which is a good signature for the importance of partonic energy loss. The parton has the possibility to become a prehadron state inside the nucleus and become absorbed on the way through cold nuclear matter. This mechanism limits the path length on which the parton can loose energy and acquire transverse momentum.

Let us now discuss jets in cold matter i.e. jets resulting from DIS on nuclei. Electron scattering on a fixed target at intermediate Bjorken x can be treated along similar lines as the DGLAP evolution of the quark jet in the cold medium, whereas electron-nucleus scattering at low x, in principle necessitates the evolution of the quark and antiquark produced from photon-gluon fusion. It is not clear whether the cascades from the two reaction products behave independently when they propagate through the target. In the Ariadne model two strings result from the quark and antiquark produced by photon-gluon fusion. The first string connects the antiquark with the quark which emitted the gluon. The

second string combines the quark with the remnant diquark of the proton. Because of the aligned jet configuration one of the two strings only contains few low momentum particles and perhaps may be neglected in first approximation. The evolution equation outlined above can then be applied to jet propagation in cold matter and Accardi and myself have started work on the above model. Scattering partners of the quark are nucleons and the quantity $< \sigma q_\perp^2 >$ can be derived from the dipole cross section on nucleons. The resulting transport parameter at Hermes energies is very small $\hat{q} = 0.035\,\mathrm{GeV}^2\,/\,\mathrm{fm}$ and has been tested in hadronic broadening of the produced hadrons [4]. For a high energy machine with an electron-nucleon energy $E_{cm} = 100\,\mathrm{GeV}$ the transport parameter will be larger due to the increasing dipole cross section, we estimate that the transport parameter will increase to about $\hat{q} = 0.1\,\mathrm{GeV}^2\,/\,\mathrm{fm}$. So effects should well be observable, but smaller than at RHIC.

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